Chapter 21

Electromagnetic induction

21.1 Inducing an electric current

OALG 21.1.1 Observe and find a pattern

In the experiments that you will analyze in this activity we use a galvanometer to detect current. You learned how a galvanometer works in Chapter 20, Activity 20.3.8

a. Watch the following video https://mediaplayer.pearsoncmg.com/assets/_frames.true/sci-phys-egv2e-alg-21-1-1 and describe what you observed. What patterns do you notice? Note that the circuit with the galvanometer does not have any battery in it.

b. Develop a rule: Devise a preliminary rule that summarizes the condition(s) needed to induce a current in a coil. What are the assumptions that you made?

c. Compare the rule you devised in part **b** to the patterns identified in Observational experiment table 21.1 in the textbook. The experiments from which the patterns emerged are at https://mediaplayer.pearsoncmg.com/assets/_frames.true/secs-experiment-video-43.

OALG 21.1.2 Test and revise your idea

The goal of this activity is to test the rule that you invented in Activity 21.1.1. In the following experiments you will have one coil (coil 1)connected to a battery/power supply through the switch. The other coil (coil 2) is connected to the galvanometer.

Experiment 1. Use the rule devised in Activity 21.1.1 part **b**. to predict what will happen if you move coil 1 relative to coil 2.

Experiment 2. Use your current rule to predict what will happen when you place a coil connected to a galvanometer next to the coil connected to the battery/power supply (so that axis of the coils coincide). Then you

(1) close the switch without moving either coil,

(2) let the current run for a period of time, and finally

(3) open the switch.

a. Describe the experiments in words and sketches and make the predictions of their outcomes using the rule you invented in Activity 21.1.1.

b. Watch both experiments here [https://mediaplayer.pearsoncmg.com/assets/_frames.true/sci-phys-egv2e-alg-21-1-2] and compare the outcomes to the predictions.

c. Make a judgment concerning the rule that you're testing. If necessary, revise your rule to incorporate your new findings. Note that your revised rule should be consistent with *all* the experiments you've conducted up to this point.

d. Compare your reasoning to the reasoning in Testing Experiment Table 21.2 in the textbook. Do you need to revise the rule?

OALG 21.1.6 Read and interrogate

Read and interrogate Section 21.1 in the textbook and answer Review Question 21.1.

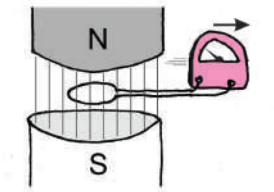
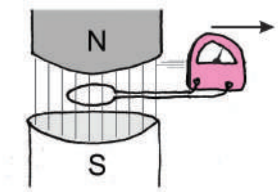
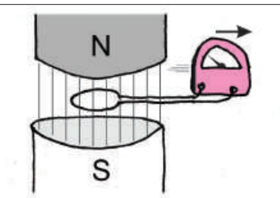
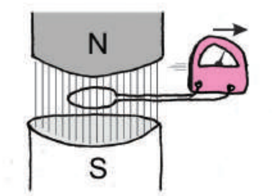
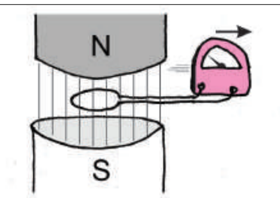
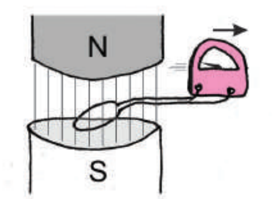
OALG 21.1.7 Practice

Answer Questions 1 and 2 on page 679 in the textbook and solve Problems 1 and 2 on page 680.

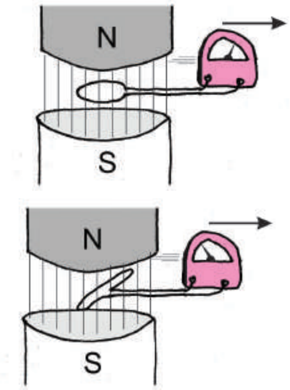
21.2 Magnetic flux

OALG 21.2.2 Observe and find a pattern

The table that follows describes five new experiments using a galvanometer, an electromagnet, and a coil. The outcomes of the experiments are included.

Experiment	**Illustration**	**Outcome**
a. Position a coil so that the $\vec{B}$ field lines are perpendicular to it and move it slowly out of the magnetic field. Repeat the experiment, moving the coil quickly.	 	The quicker the coil's motion, the larger the induced current.
b. Position the magnet and the coil as in experiment **a**. and move the coil slowly out of the magnetic field. Repeat the experiment using a stronger magnet.	 	A stronger magnet induces a stronger current in the coil compared to a weaker magnet when the coils move at the same speed with respect to the magnet.
c. Position a magnet perpendicular to the coil and the coil as in experiment **a**. and move the coil slowly out of the magnetic field. Then position the coil so that the plane of the coil makes some other angle with the $\vec{B}$ field lines. Keep the speed the same.	 	When the $\vec{B}$ field lines are perpendicular to the plane of the moving coil, the strongest current is induced.

Experiment	**Illustration**	**Outcome**

d. Use two identical coils. Fold part of the wire of one coil to make a loop with a smaller area (see the figure). Position each coil and the magnet as in experiment **a**. Move the coils out of the magnetic field at the same speed with respect to the magnet.		A stronger current is induced in the coil with the larger area.

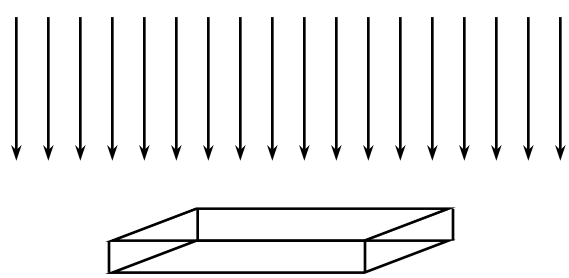
a. Devise a mathematical expression that relates the *magnitude* of the induced current to various properties of the magnetic field, relative motion of the coil with respect to the magnet, and properties of the coil.

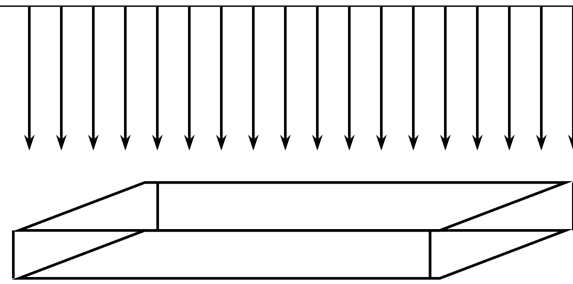
b. Compare the expression that you devised

OALG 21.2.3 Reason

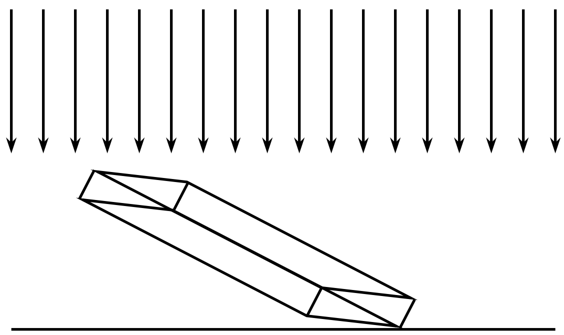
Imagine that rain is falling at a rate of 100 drops per second, per square meter (100 drops/s/m^2).

a. In each of the following three scenarios, estimate how much rain (in units of drops) you will collect in 1 minute in the box. You should assume the rain falls vertically.

Scenario 1: Box is 2 m wide, 1 m long. 
Scenario 2: Box is 3 m wide, 2 m long



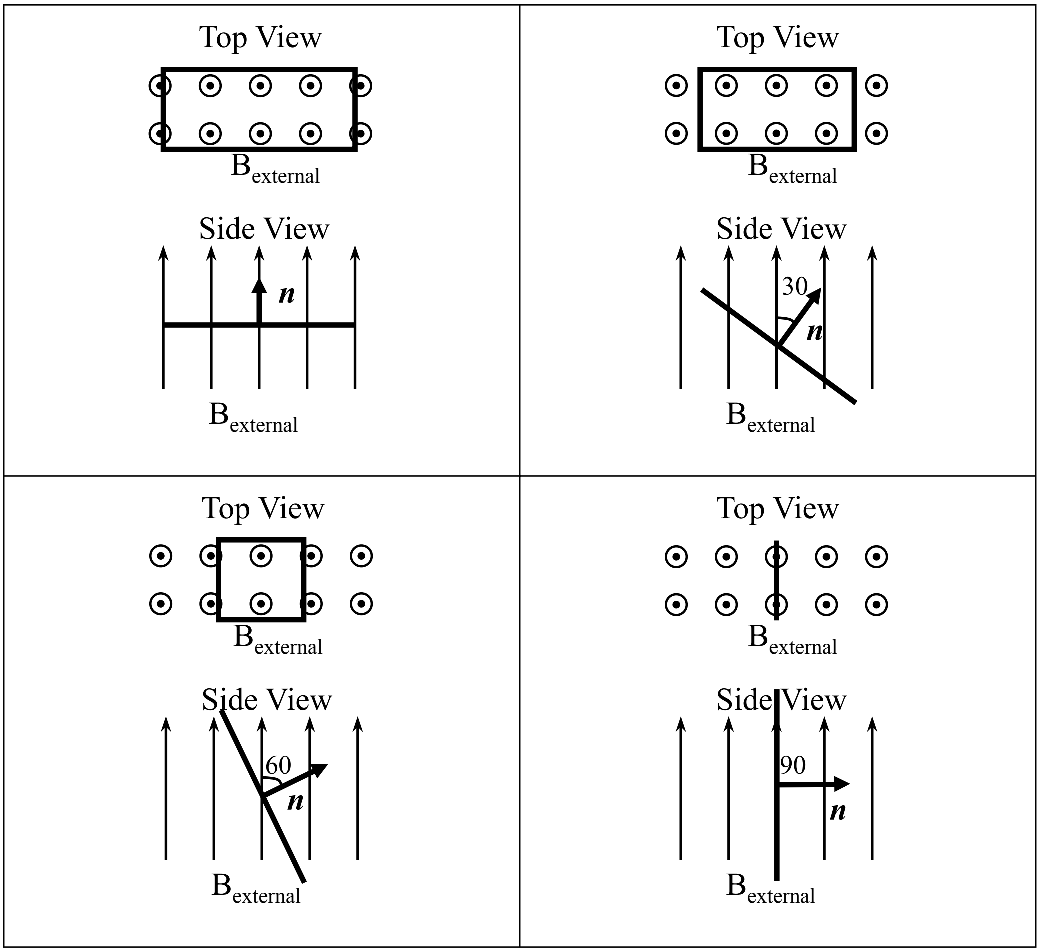
Scenario 3: Box is 2 m wide, 1 m long, and tilted 30° above the horizontal. (Ignore any issue of spillage).



b. How would you adjust your answers if the rain was not falling vertically, but, say, at an angle of 30° from the vertical (assume that in the Scenario 3 the rain falls perpendicularly to the box bottom)?

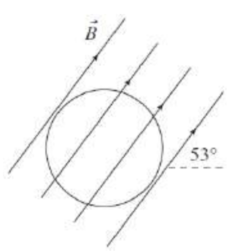
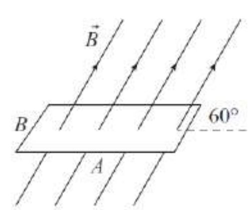
OALG 21.2.4 Represent and Reason

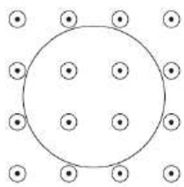
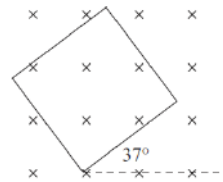
Calculate the flux of magnetic field lines passing through the rectangular loop in each of the cases shown below. The loop has dimensions L m long by W m wide. The magnitude of the $\vec{B}_{\text{external}}$ field is B_{external} (in T). Leave your answer in terms of L, W, B_{external} and $\cos\theta$.



OALG 21.2.5 Reason

The magnitude of the $\vec{B}$ field in each situation described below is 0.50 T. For each situation in this table, working with your group members, calculate the magnetic flux through the loop.

Situation	**Situation**
Loop and $\vec{B}$ are in the same plane as the paper. The radius of the circular loop is 5.0 cm. 	Loop perpendicular to the paper and $\vec{B}$ in the plane of the paper. Side A = 0.2 m, side B = 0.1 m. 

Loop is in the same plane as the paper, and $\vec{B}$ out of paper. The radius of the circular loop is 5.0 cm. 	Square loop of side A = 0.1 m is in the same as the plane of the paper. $\vec{B}$ into the paper. 

OALG 21.2.6 Read and interrogate

Read and interrogate Section 21.2 in the textbook and answer Review Question 21.2.

OALG 21.2.7 Practice

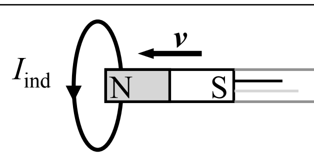
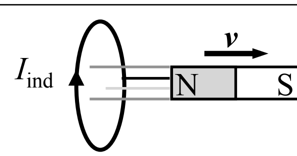
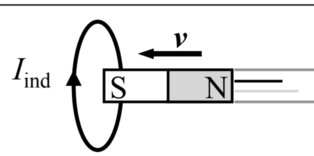
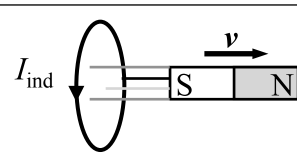
Answer Questions 4 and 5 on page 679 and solve Problems 8 and 9 on page 680.

21.3 Direction of the induced current

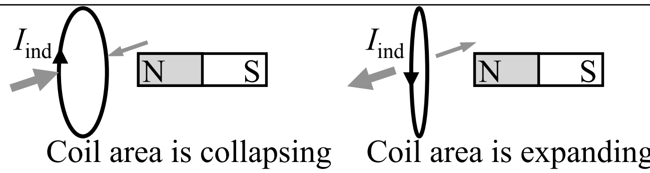
OALG 21.3.1 Observe and find a pattern

The experiments below repeat earlier experiments that used a galvanometer, a bar magnet, and a coil and in which a current was induced. The direction of the induced current is shown in the illustrations.

a. Analyze the 6 experimental scenarios in the table below. For *each* case, on your whiteboard, draw $\vec{B}_{\text{ext}}$ field vectors through the coil caused by the moving magnet. Indicate whether the external $\vec{B}_{\text{ext}}$ field vectors through the coil are decreasing or increasing in magnitude. Draw induced magnetic field vectors $\vec{B}_{\text{ind}}$ created by the induced current in the coil.

Experiments:	
	
	

Experiments:



b. Devise a rule relating the direction of the induced current in the coil and the change of external magnetic flux through it. *Hints:* (1) Focus on the direction in which $\vec{B}_{ext}$ is changing rather than the direction of $\vec{B}_{ext}$ itself. (2) Compare the direction of the induced magnetic field vectors $\vec{B}_{ind}$ in relation to $\Delta\vec{B}_{ext}$.

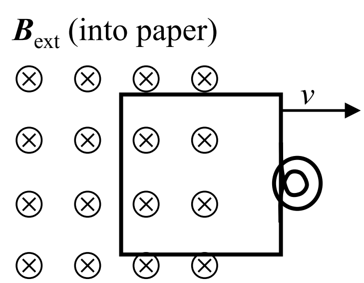
c. Formulate a general rule: How does the direction of the induced current in a coil relate to the *change* of external magnetic flux through it?

d. Watch the following video https://youtu.be/TikiH3WR54E Describe what you observed. Use your rule from part **c** to explain the observations.

OALG 21.3.2 Read and interrogate

Read Section 21.3 in the textbook and answer Review Question 21.3.

OALG 21.3.3 Practice

Carefully follow the steps below in the order presented to determine the direction of an induced current using Lenz's rule. In this particular example, you are pulling a coil out of a region with an external magnetic field that points into the paper (the crosses).	

a. Redraw the diagram in your notes. Identify the external magnetic field, $\vec{B}_{ext}$, and decide if the external magnetic flux through the loop is increasing or decreasing as the coil moves.

b. Draw the induced magnetic field inside the coil, $\vec{B}_{ind}$, so that it *opposes the change* in external magnetic flux through the loop. Think about how $\vec{B}_{ind}$ can *oppose* an increase or decrease in external magnetic flux.

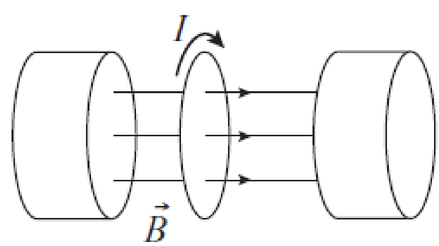
3. Use the right-hand rule for the direction of a magnetic field created by a current (review Section 20.2, page 620 in the textbook) to determine the direction of the induced current I_{ind}. I_{ind} must circulate to create $\vec{B}_{\text{ind}}$. Curl your fingers in the direction of $\vec{B}_{\text{ind}}$ so that your thumb is aligned with one of the wires, and look at the direction of your thumb: That is the direction of I_{ind}. Draw the direction of I_{ind} on your diagram.

OALG 21.3.4 Practice

Answer Questions 5 – 8 on page 679 and solve Problems 13 and 14 on page 681.

21.4 Faraday's law of electromagnetic induction

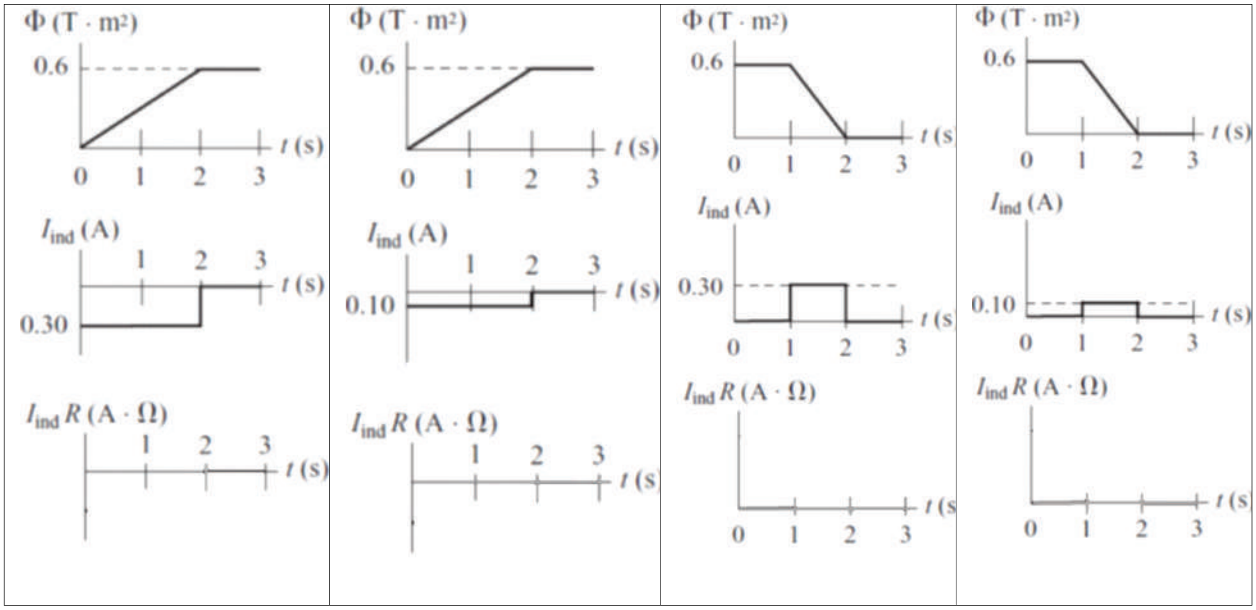
21.4.1 Observe and explain



In the table that follows, the results of four experiments are shown in which a changing magnetic field produced by an electromagnet passes through a loop, as illustrated to the right. This changing $\vec{B}$ field causes a changing flux Φ through the loop and an induced current I_{ind} around the loop of resistance R. The product $I_{\text{ind}}R$ is also plotted as a function of time.

a. Draw the third graph that shows the product $I_{\text{ind}}R$.

Coil resistance is 1.0 Ω	Coil resistance is 3.0 Ω	Coil resistance is 2.0 Ω	Coil resistance is 6.0 Ω



b. Discuss what the meaning of the product $I_{ind}R$ is and which equivalent quantity this product may represent. Then devise a relationship between $\frac{\Delta\Phi}{\Delta t}$ and that quantity. Do not forget the sign to indicate direction!

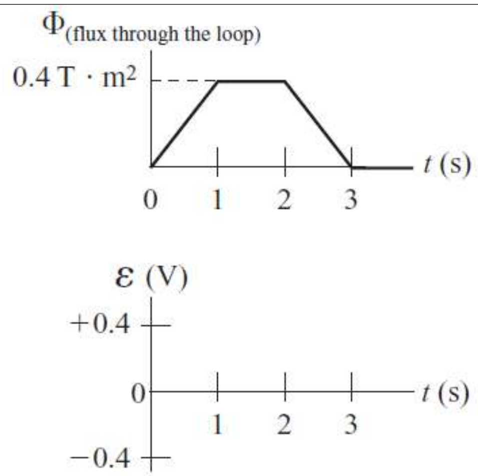
OALG 21.4.2 Read and interrogate

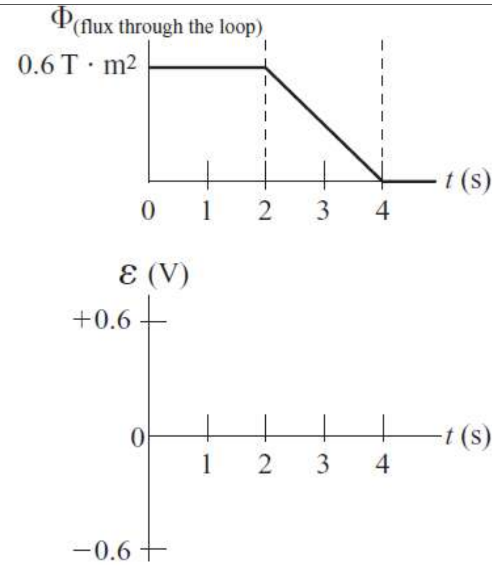
Read and interrogate Section 21.4 in the textbook and answer Review Question 21.4.

OALG 21.4.3 Represent and reason

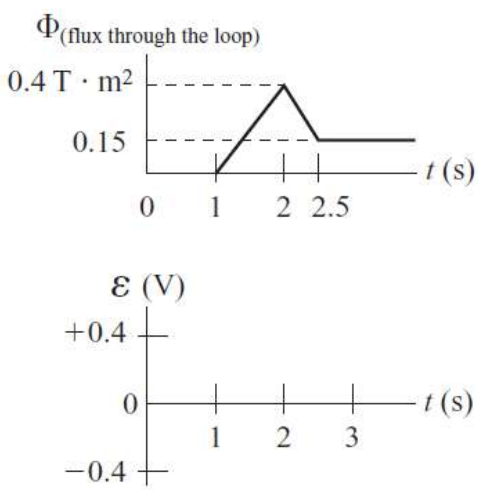
Four situations are shown in which the external flux through a loop is plotted as a function of time. In the table that follows, draw another graph that shows the induced emf in the loop as a function of time.

Situation 1	**Situation 2**

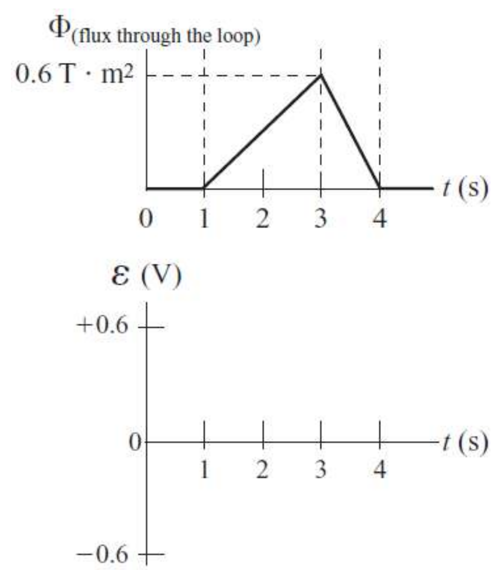




Situation 3

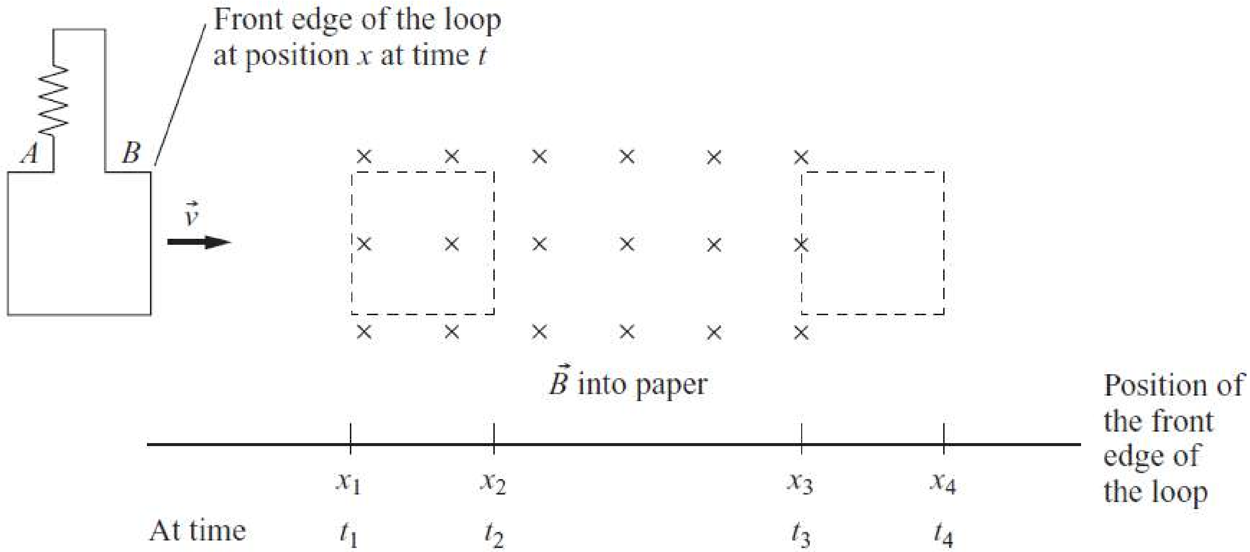


Situation 4

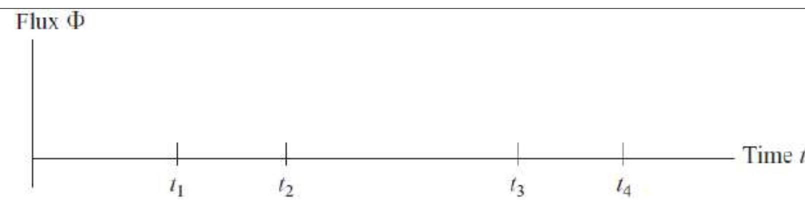
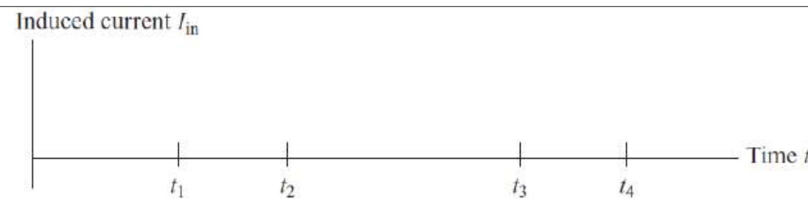


OALG 21.4.4 Represent and reason

A rectangular loop with a resistor is pulled at constant velocity through a uniform external magnetic field that points into the paper in the regions shown in the illustration with the crosses (×).



Plot graphs of flux and induced current versus time, consistent with the process above.

a. Draw a qualitative flux-versus-time graph for the process (positive in and negative out).	
b. Draw a qualitative induced current-versus-time graph for the process.	

OALG 21.4.5 Practice

Answer Questions 9, 12, and 15 on pages 679-680 and solve problems 16-18, 23, 25 and 28 on page 681.

21.5 Skills for analyzing processes involving electromagnetic induction

OALG 21.5.1 Regular problem

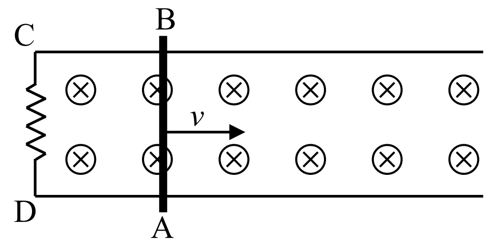
Use the steps in the table below to solve the problem. Then compare your solution to the solution in the Example 21.5 in the textbook.

To determine the $\vec{B}$ field produced by an electromagnet, you use a 30-turn circular coil of radius 0.10 m ($30\text{-}\Omega$ resistance) that rests between the poles of the magnet and is connected to an ammeter. When the electromagnet is switched off, the $\vec{B}$ field decreases to zero in 1.5 s. During this 1.5 s the ammeter measures a constant current of 180 mA. How can you use this information to determine the initial $\vec{B}$ field produced by the electromagnet?

Sketch and Translate • Create a labeled sketch of the process described in the problem. Show the initial and final situations to indicate the change in magnetic flux. • Determine which physical quantity is changing ($\vec{B}$, A, or θ), thus causing the magnetic flux to change.	
Simplify and Diagram • Decide what assumptions you are making: Does the flux change at a constant rate? Is the magnetic field uniform? • If useful, draw a graph of the flux and the corresponding induced emf-versus-clock reading. • If needed, use Lenz's law to determine the direction of the induced current.	
Represent Mathematically • Apply Faraday's law and indicate the quantity ($\vec{B}$, A, or the $\cos\theta$) that is resulting in a changing magnetic flux. • If needed, use Ohm's law and Kirchhoff's loop rule to determine the induced current.	
Solve and Evaluate • Use the mathematical representation to solve for the unknown quantity. • Evaluate the results—units, magnitude, and limiting cases.	

OALG 21.5.2 Regular application

A *horizontal* metal bar is pulled at constant velocity of 2 m/s through a 0.5 T *downward*-pointing magnetic field. The bar slides on two *horizontal*, frictionless metal rails moving away from a resistor connected between the ends of the rails. (The distance between the rails is 0.50 m.) Find the induced current through the resistor of resistance $R = 10\ \Omega$ in terms of any or all quantities given. (The top view of the set-up is shown below.)



Work with your group-mates to answer the following questions to figure out the induced current in the circuit.

a. Describe the assumptions you are making.

b. Plot a graph of flux through the area surrounded by rails, the moving bar and the resistor at the end of rails as a function of time.

c. Draw a consistent emf-versus-clock-reading graph.

d. Represent the flux, change in flux, and emf mathematically.

e. Combine the mathematical representation with Ohm's law to get the desired result for the current.

f. Check out Example 21.7 in the textbook. How does this approach compare to the approach used in the example?

OALG 21.5.3 Equation Jeopardy

Collaborate with your group to write a problem in words and construct a sketch for a phenomenon involving electromagnetic induction that is described by each equation below (there is more than one possibility). Provide all the details for this phenomenon on your whiteboard and share with another group.

Process 1: $\varepsilon = -20\left(\pi\left(0.10\ \text{m}\right)^2\right)\cos 37°\dfrac{\left(0-0.40\ \text{T}\right)}{\left(2.0\ \text{s}-0\right)}$

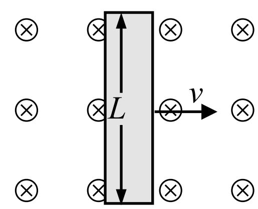
Process 2: $\varepsilon = -4\left(0.40\ \text{T}\right)\cos 0°\dfrac{\left(0-\left(0.10\ \text{m}\times 0.20\ \text{m}\right)\right)}{\left(2.0\ \text{s}-0\right)}$

a. For each process, write word description in words of a problem that you can solve using this equation.

b. Sketch a situation or process that the equation might describe.

21.5.4 Observe and explain

The analysis of the following experiment will help you devise an expression for the emf produced in a loop moving into, through, and out of a magnetic field. This is called *motional emf.*

A metal bar of length L moves at constant speed v through a magnetic field B that points into the paper (the crosses).	

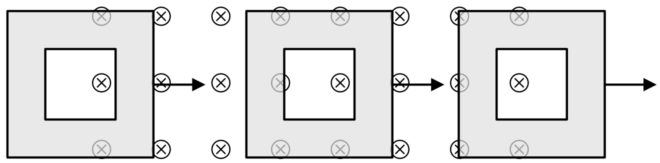
a. Indicate on the bar (redraw it on your whiteboard) how the charged particles in the bar are redistributed due to the force that the magnetic field exerts on them.

b. This charge redistribution from part **a**. produces an electric field inside the bar that prevents further charge redistribution. Draw the $\vec{E}$ field lines inside the bar.

c. Apply Newton's second law to a test charge in the middle of the bar—now it is in an electric field and in a magnetic field, and it is in equilibrium.

d. Use the expression that relates E_y and the potential difference over a distance $\Delta V/L$ with the previous results to determine an expression for the emf (potential difference) between the ends of the bar.

e. Below, you see a rectangular metal conductor first entering the magnetic field, later completely in the magnetic field, and finally leaving the magnetic field described above. Use the results of parts **a**. and **b**. to draw charge distributions on the front and back vertical parts of the rectangle due to the force of the magnetic field on charge in the metal. *Note*: The magnetic field only exerts forces on charges in the metal parts that are in the field, not on those outside the fields. Will there be a current in the conductor? If so, indicate the direction.



f. Use the results of part **d**. to write an expression for the potential difference induced around the rectangular metal conductor while entering the field.

g. Use the results of part **d**. to write an expression for the potential difference induced around the rectangular metal conductor when completely in the field. Note that there are now charge distributions that cancel.

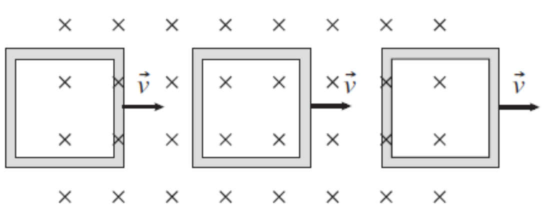
h. Use the results of part **d**. to write an expression for the potential difference induced around the rectangular metal conductor while leaving the field.

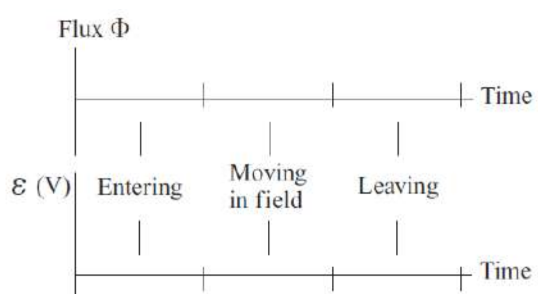
i. Read and interrogate section "Motional emf" on page 666 in the textbook.

OALG 21.5.5 Observe and explain

Repeat the previous activity, only this time use the ideas of flux and induced emf. When you are finished, check to see if the results are consistent with those in Activity 21.5.4.

<table>
<tr><th>Experiment</th><th>Analysis</th></tr>
<tr><td>The same rectangular metal conductor as in Activity 21.5.4 part e. is entering the magnetic field, moving completely in the magnetic field, and leaving a magnetic field that points into the paper. The rectangle moves with constant velocity.


</td><td>a. Draw a graph showing the magnetic flux through the opening of the metal conductor as a function of time while the rectangle is entering the magnetic field, moving completely in the magnetic field, and leaving the magnetic field. Then use the flux graph to make a graph of the induced emf for the same time interval.



</td></tr>
</table>

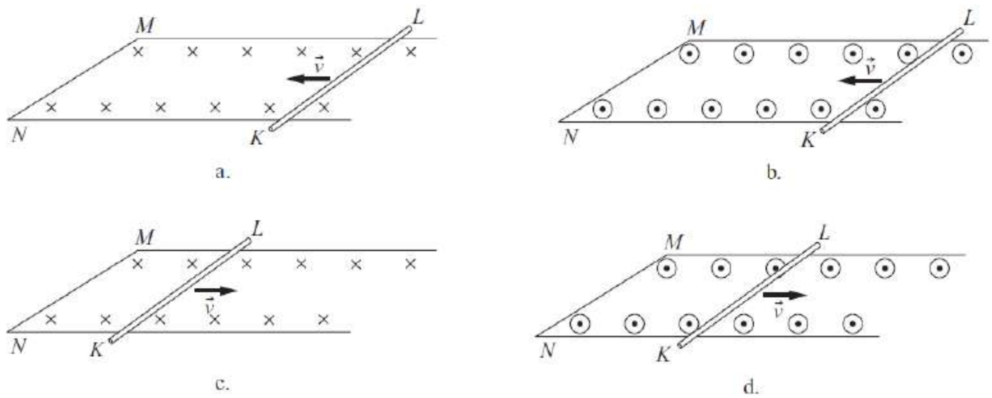
b. Write an expression for the flux as a function of time as the rectangle enters the field. Then use this expression to determine the emf while the rectangle is entering the field.

c. Write an expression for the flux as a function of time as the rectangle completely in the field. Then use this expression to determine the emf while the rectangle is in the field.

d. Compare the expressions in parts **b.** and **c.** with the expressions determined in 21.5.4 parts **f**. and **g**. (We are skipping the calculation for when the rectangle is leaving the field—it's a little more messy.)

OALG 21.5.6 Reason

Loop *KNML* is made of metal rods, where rod *KL* slides at a constant speed on the side rods *NK* and *ML* in the direction indicated by the arrow. A constant external magnetic field either points down into the loop (the crosses) or up out of the loop (the dots), perpendicularly to the plane of the loop. For each situation, use two different methods to determine the direction (not the magnitude) of the electric current in loop.



a. Use the magnetic force on free charges in the rod to find

(1) the charge separation on the rod,

(2) the electric force that this charge separation produces that prevents additional charge separation, and

(3) the relationship between the electric field caused by the charge separation and electric potential difference to determine which side of the moving rod is at higher electric potential and the direction of the current around the loop.

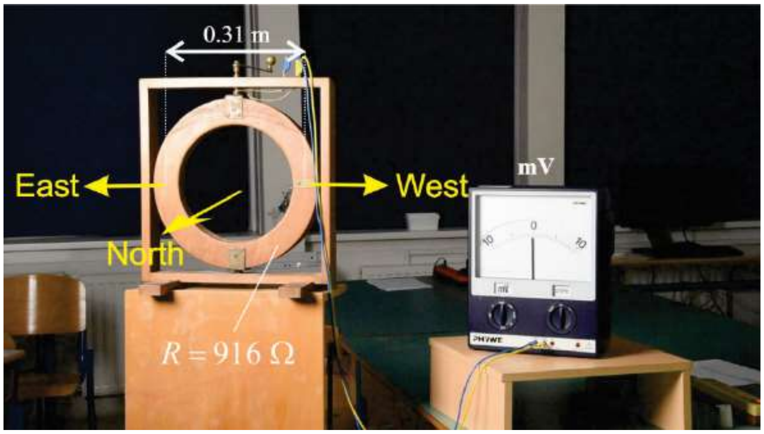
(4) Draw the directions of the currents in the figures above.

b. Next use Lenz's law and right-hand rule for the magnetic field to determine the directions of the induced currents. Draw the directions of the current determined with this method in the figures above using a different-colored pencil.

c. Do these two approaches agree? Explain.

OALG 21.5.7 Real-world application

You have a large coil with 1500 turns of copper wire and a voltmeter that can measure potential differences between –10 mV and 10 mV. The average diameter of the coil is 0.31 m and the resistance of the coil is $916\ \Omega$. The coil is mounted in the wooden frame so that it can rotate around the axis that coincides with the coil diameter. The video [https://mediaplayer.pearsoncmg.com/assets/_frames.true/sci-phys-egv2e-alg-21-5-14] shows two experiments. In both experiments, the voltmeter is connected to the coil ends. The experiments were performed on the Northern hemisphere. The photo below shows the initial orientation of the coil (the normal to the plane of the coil points towards the geographical North).



a. Watch the video and, collaborating with your group-mates, propose a qualitative explanation for the outcome of both experiments. Make sure your group's explanation accounts for all changes in the magnitude and in the sign of the voltmeter reading.

You can treat the voltmeter as a device that measures potential difference across its own internal resistor, which has very large resistance (several megaohms). If you connect such a voltmeter across the coil as shown above and an induced emf appears in the coil, then the voltage measured by the voltmeter is equal to the induced emf in the coil.

b. Make a list of physical quantities that you can estimate based on data given above and analyzing the video. The video was recorded at 30 frames per second. (*Note*: for a vector quantity, you can estimate its magnitude, direction or both). Estimate two of them.

OALG 21.5.8 Practice

Solve Problems 31-33, 39, and 41-42 on page 682.

21.6 AC circuits

OALG 21.6.1 Read and interrogate

Read and interrogate Section 21.6 in the textbook and answer the following questions.

a. Why is the output power of a resistor in an AC circuit not zero, but the output powers of a capacitor and an ideal inductor are zero?

b. What might be the reasons for using such high frequencies in the videos of experiments in this section?

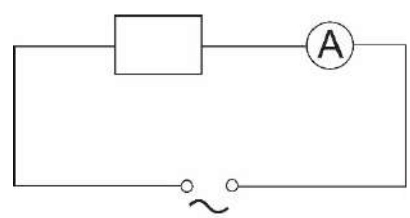
c. What is the meaning of the notation "*rms*" in AC circuits and why is this notation needed?

d. Answer Review Question 21.6.

OALG 21.6.2 Apply

Imagine that you have the equipment on the list below and perform the experiment described below.

Equipment: a resistor (R), a capacitor (C), an inductor (L) with negligible resistance, an AC source with voltage of adjustable amplitude (V_0) and frequency (f), and an ammeter that measures the root-mean-square value of AC current (I_{rms}).



$$\Delta V = V_0 \sin(2\pi f \times t)$$

Experiments: You build a circuit shown in the figure on the right, connecting one of the elements (R, C and L) at a time in the place of the box.

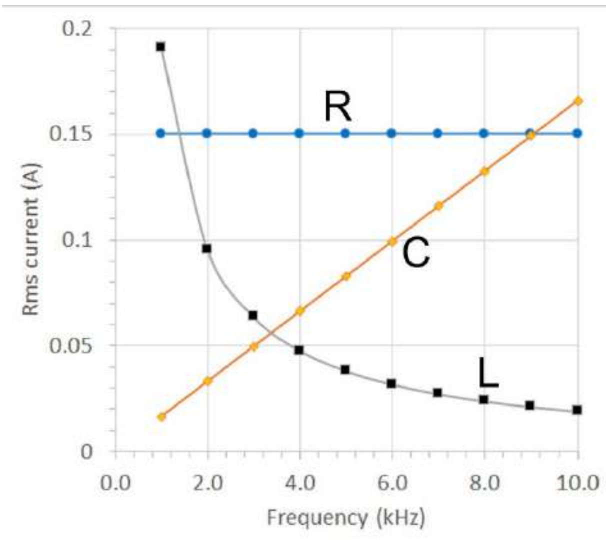
For each element, you perform the following experiments:

Experiment 1: You keep the amplitude of the AC voltage constant at 12 V and change the frequency of the AC source from 1 kHz to 10 kHz in steps of 1 kHz. At each frequency, you measure the I_{rms} through the circuit.

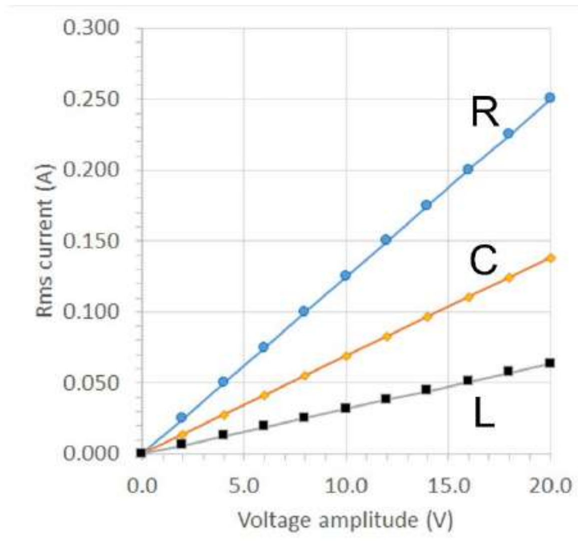
Experiment 2: You keep the AC voltage frequency constant at 5000 Hz and change the amplitude of the AC source from 0 V to 20 V in steps of 2 V. At each voltage setting, you measure the I_{rms} through the circuit.

The graphs of the measurements are shown below:

Experiment 1:



Experiment 2:



a. Describe in words how the reactance of each element depends on the frequency of AC source and how it depends on the voltage amplitude of the AC source.

b. Determine the reactance of each element.

c. Determine the resistance of the resistor R, the capacitance of the capacitor C and the inductance of the inductor L.

d. Describe the features of the graphs above that indicate that the two graphs are consistent with each other for each element.

e. If you repeat Experiment 2 using the AC frequency of 10,000 Hz and keeping the other quantities as in the original experiment, how would the graphs of rms current versus voltage amplitude change? Draw the expected new graphs (all three on one coordinate system, as shown above).

f. The equation $\Delta V = 10\ \text{V} \times \sin(2\pi \times 5 \times 10^3\ \text{s}^{-1} \times t)$ describes the time dependence of the voltage of an AC source. Write three equations that describe the time dependences of the current through the elements R, C and L respectively. Do not forget the phase shifts between voltage and current!

g. You make a new element by connecting the resistor R and the inductor L (the same elements that were used above) in series. For what range of frequencies will this element behave almost like an ideal inductor (i.e. an element with a negligible ohmic resistance)? Indicate any assumptions that you made.

OALG 21.6.3 Apply

You have an open parallel-plate capacitor, which has two metal plates and air between them. You can insert slabs of dielectric materials that fit into space between the metal plates (all slabs have the same size). You also have the following equipment: an AC source, an ammeter that measures the root-mean-square value of the AC current, and a parallel-plate capacitor of unknown capacitance.

a. Brainstorm what experiment you could design that will allow you to determine the dielectric constant of the slabs.

b. Describe in detail the measuring procedure and the steps that will allow you to determine the dielectric constants.

OALG 21.6.4 Apply

You have several cylinders of the same size made of different materials and the following equipment: an AC source, an ammeter that measures the root-mean-square value of the AC current, and a solenoid into which the cylindrical samples fit snuggly. The inductance of the solenoid is not known.

a. Brainstorm what experiment you could design that will allow you to determine magnetic permeability of the cylinders.

b. Describe in detail the measuring procedure and the steps that will allow you to determine magnetic permeability of the cylinders.

c. If you could choose between several solenoids that have different resistances and inductances, which solenoid would you choose? Explain.

OALG 21.6.5 Explain

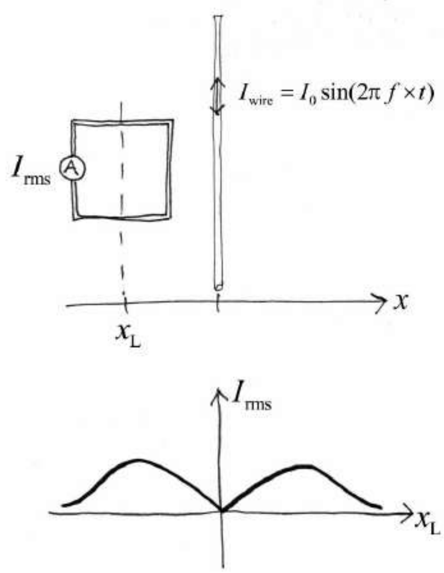
An AC electric motor consists of several coils, some in the rotating part (rotor) and some in the stationary part of the motor (stator). The label on the electric motor says that the motor is designed to operate at 120 V AC.

a. Describe what might happen to the motor if you connect the same motor to a 120 V battery (a DC source) that has very small internal resistance.

b. Explain why what you said in part **a.** will happen.

OALG 21.6.6 Apply

Imagine the following experiment. You connect a long, straight wire to an AC power supply that creates current $I_{\text{wire}} = I_0 \sin(2\pi ft)$ through the wire. You have a square loop which is connected to an ammeter that measures rms current through the loop (see the figure below). You keep the wire fixed on a table and place the loop on the table as shown in the figure below. Then you start moving the loop so that the coordinate x_{L} for the position of the center of the loop changes. For every x_{L} position of the center of the loop, you record I_{rms} through the loop (the loop is at rest while you are recording the current). Then you shift the loop in the x-direction to a new position and repeat the measurements. A qualitative graph at the bottom of the figure shows the result of your measurements.



a. Work with your group members to devise a qualitative explanation for the shape of the graph. Account for important features of the graph such as zero current, maximum current, and limiting cases.

b. Imagine that you repeat the original experiment with an AC current through the wire that vibrates with amplitude I_0 and frequency $2f$. Work with your group members to predict how the I_{rms}-versus-x_L-graph will look in this case. Copy the previous graph to your notebook and draw the expected curve on it.

c. Imagine that you repeat the original experiment with a DC current I_0 through the wire. How will the I_{rms}-versus-x_L-graph look in this case? Add the expected curve on the graph that you drew in part **b**.

OALG 21.6.7 Practice

Solve Problems 43-46 on page 682.

21.7 Transformers

OALG 21.7.1 Reading exercise

Read Section 21.7 in the textbook and answer the Review Question 21.7.

OALG 21.7.2 Find a pattern and explain

You have a transformer that has a fixed primary coil $(N_p = 1000)$ and allows you to change the secondary coils. You have set of five secondary coils with the number of turns from 100 to 500 in steps of 100. With each secondary coil you perform the following experiment.

You connect the primary coil to a 120 V AC source and a $20\ \Omega$ resistor to the secondary coil. Then you measure the current through the primary coil (I_p), current through the secondary coil (I_s), and the voltage across the resistor (i.e. secondary coil, ΔV_R). The data are shown in the table below. All currents and voltages are rms values.

$\varepsilon_p(V)$	$I_p(A)$	N_p	N_s	$\Delta V_s(V)$	$I_s(A)$
120	0.060	1000	100	12	0.600
120	0.240	1000	200	24	1.200
120	0.540	1000	300	36	1.800
120	0.960	1000	400	48	2.400
120	1.500	1000	500	60	3.000

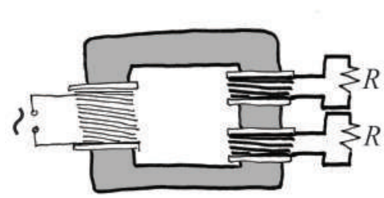
a. Identify a pattern relating the ratio $\frac{\Delta V_R}{\varepsilon_p}$ and the ratio $\frac{N_s}{N_p}$ and express it as an equation.

b. Based on your finding in part **a.** predict the emf in the primary coil if the secondary coil with 500 turns is connected to the 120-V AC source.

c. Identify a pattern relating the ratio of the currents $\frac{I_s}{I_p}$ and the ratio of the numbers of turns $\frac{N_s}{N_p}$ and express it as an equation.

d. Compare the input power of the transformer with the output power. Does it make sense? How do you think these powers will relate for the transformer that becomes warm after connecting the resistor to the secondary coil?

e. Your friend says: "If we put two 300-turn coils as secondary coils on the same iron core and connect identical resistors to each of them (see the figure below), then the total output power of the transformer will be the same as if we connected two such resistor in series to the 600-turn secondary coil alone." Do you agree with your friend? If not, explain what is wrong about their reasoning and provide a correct answer with an explanation.



OALG 21.7.3. Explain

A transformer is designed to be connected to a 120-V AC source. What might happen to the transformer if you connect its primary coil to a 120-V DC source with very small internal resistance and leave the secondary coil connectors open? Describe qualitatively the current through and the voltage across the primary coil, and the current through and voltage across the secondary coil.

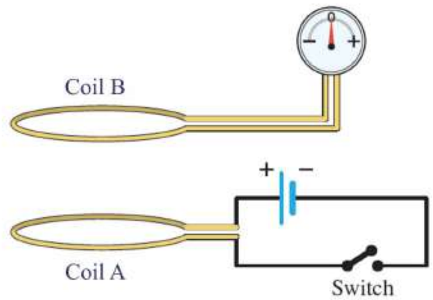
OALG 21.7.4 Practice

Solve Problems 49, 51, and 52 on pages 682-683.

21.8 Mechanisms explaining electromagnetic induction

OALG 21.8.1 Explain

You have a coil A connected to a DC power supply through a switch. You have another coil B that is connected to a galvanometer and parallel to the coil A, as shown in the figure below.



a. Explain why there is electric current in coil B when you open and close the switch, although there is no battery in coil B's circuit. What can play the role of the battery for B's circuit?

b. Imagine you removed coil B but still opened and closed the switch connected to coil A. What is happening in the space surrounding coil A? Draw electric field lines for the situation when you close the switch and when you open the switch.

c. How are these lines different from the electric field lines you learned before in Chapter 18?

OALG 21.8.2 Read and interrogate

Read and interrogate Section 21.8 in the textbook and answer Review Question 21.8.